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Energy, Mines and Resources Canada

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A COMPARISON OF THE ENERGY AND PRODUCT DISTRIBUTION FROM BIOMASS GASIFIERS IN CANADA

RENEWABLE ENERGY DIVISION

PREPARED FOR:

Bioenergy Development Program
Renewable Energy Division
Coal and Alternative Energy Branch
Energy, Mines and Resources Canada
DSS Contract File No: 02SQ.23216-4-6431
September 2, 1985

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SUMMARY

A detailed analyses of the raw producer gas streams generated by a downdraft gasifier and by a fluidized-bed gasifier are presented and are discussed in terms of raw gas clean-up considerations and of energy conversion efficiency.

The major gasifier operating parameters such as fuel/air ratio, carbon conversion efficiency, net energy conversion efficiency, and producer gas heating value are then compared between seven operational gasifiers and a computer simulation model of a fluidized-bed gasifier developed by Queen's University.

It is concluded that the Queen's University model correctly predicts that the fuel/air ratio is the single most important parameter for determining gasifier performance. Downdraft gasifiers exhibit superior energy conversion efficiency and producer gas quality because they utilize a higher fuel/air ratio than do fluidized bed gasifiers.

It is recommended that the applicability of the downdraft gasifier for use in northern Canadian communities be evaluated using current economic conditions.

A process for scrubbing the raw producer gas condensate is outlined. It should be developed so that the gasifier effluent is environmentally acceptable.

RESUME

Ce rapport détaille le résultat d'analyses réalisées sur des gazs non-traités de deux types de gazogène: le gazogène inversé et le gazogène à lit fluidisé. Les moyens requis pour la purification des gazs de synthèse ainsi que les rendements thermiques y sont également exposés.

Les principaux paramètres impliqués lors du fonctionnement de sept gazogènes actuellement en activité ont été comparés avec les résultats obtenus par simulation sur ordinateur de l'opération d'un gazogène à lit fluidisé, simulation mise au point par l'Université Queen. Parmi les paramètres étudiés figure le rapport combustible/air, le degré d'oxydation du combustible, le rendement thermique global du procédé et la valeur calorifique des gazs de synthèse.

La conclusion tirée de la simulation réalisée par l'Université Queen confirme que le rapport combustible/air est en fait le facteur essentiel à considérer lors de l'évaluation du rendement d'un gazogène. Ce rapport étant plus élevé pour les gazogènes de type inversé, ceux-ci se sont donc révélés supérieurs aux gazogènes à lit fluidisé tant au niveau rendement thermique que par la qualité des gazs produits.

Il serait donc opportun d'évaluer l'utilisation de gazogènes de type inversé dans les communautés du Nord canadien, dans les conditions économiques qui y prévalent actuellement.

Ce rapport décrit également un prodédé de purification des liquides condensés engendrés lors de la production des gazs de synthèse. Des études plus poussées devraient être entreprises afin de produire des effluents de gazéification épurés.

ACKNOWLEDGEMENTS

Much of the data presented in this report was derived during earlier ENFOR funded projects. We gratefully acknowledge the important contribution of these people:

Dr. David Fung (CANMET) - Scientific Authority

Dr. Jim Hsu (Queen's University) - Gasifier theoretical modelling

Merv Aiken (B.C. Research) - Gasifier sampling

Elizabeth McDonald (B.C. Research) - Sample analysis

Lloyd Phillips (University of B.C.) - Mass and energy balances

Dr. Don Huffman, Dr. John Kryla, Art L'Ecuyer, and Ron Therberge (Forinteck East) - Operation of the Forintek down-draft gasifier

Dr. Hughes Menard (University of Sherbrooke) - HPLC tar analysis

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1.0 INTRODUCTION

Two major types of gasifiers are available commercially at present. The cocurrent or downdraft versions are being used in small internal combustion engine applications for sawmills, remote communities, and to satisfy developing nation needs for power sources. Although this type of gasifier derives from WWII German technology, it has subsequently experienced considerable research and development both in North America and in Europe.

The fluidized-bed gasifier has also recently entered commercial service where it is more appropriate for the large scale conversion of biomass to producer gas or to other products.

The gasification process produces a hot, dirty gas stream containing organic aerosols, inorganic particulates, condensable organic vapours, noncondensable gases, and water vapour. The gas stream generally has to be cleaned prior to further processing or prior to use in an internal combustion engine. (An exception is the situation where the gasifier is close-coupled to an external combustion chamber). A detailed knowledge of the composition of the raw producer gas stream is essential to the proper engineering of subsequent gas handling and cleanup equipment.

This report will therefore focus on a detailed analysis of the raw producer gas stream generated by both a downdraft gasifier and by a fluidized-bed gasifier. The gasifier operating parameters and product distribution will then be compared with other gasifiers and with the results of a computer simulation model.

A previous B.C. Research project carried out under contract to Techwest Enterprises Ltd. (ENFOR Project C-172) developed standard sampling and analytical methodology for biomass gasifiers. This work led to the C-172 document "A Workbook for Biomass Gasification Sampling and Analysis". The Workbook details procedures which yield

accurate data for evaluating gasifier performance. The application of the 'Workbook' methodology to a downdraft gasifier is described in the ENFOR C-172 report "Testing the Prototype Sampler on a Downdraft Biomass Gasifier", October, 1983. The detailed 'Workbook' methodology was subsequently simplified to a "fill-in-the-blanks" approach and is available as the ENFOR C-172 document "A Manual for Evaluating Biomass Gasifiers", March 1984.

Much of the detailed data presented in this report is derived from the above ENFOR documents.

2.0 DOWNDRAFT GASIFIER PRODUCT STREAM

Sampling and analysis were carried out on a downdraft gasifier located at Forintek Canada Corp. (Ottawa, Ontario).

The Forintek mobile wood gasifier is a prototype demonstration unit manufactued by Biomass Corporation, Yuba City, California. Purchased in 1979, it has been operated for over 500 hours in an intensive research program to test its capability to handle a variety of wood chip and residue fuels.

The moving bed downdraft unit is trailer-mounted and is rated at 1055 MJ/hr. The feed enters the top of the unit through a pressure controlled hopper. Air enters the reactor via eight tuyeres located just above the choke plate. Ash and char pass horizontally through the spaces in a slowly rotating eccentric grate and are swept to the char exit in the bottom of the reactor. The gas produced passes downward through the grate and then upward in the outer reactor annulus, giving up heat to the incoming air and to the fuel charge before exiting near the top of the reactor. The gases then pass through a dry cyclone collector where large particulates are removed and collected in a sealed container. For the sampler tests, a natural draft afterburner following the cyclone was bypassed by a 7 cm diameter stack to allow sampling of the raw producer gas. The gas discharge was flared after the sampling tee. Heating value of the dry, clean, cool gas from the unit has varied from 5.4 to 7.5 MJ/m^3. Typical gas composition has been hydrogen 16%, carbon monoxide 20%, methane 2%, other hydrocarbon gases 1%, carbon dioxide 13%, oxygen 1% and nitrogen 47%.

Table 1 summarizes the operating conditions for the gasifier during the run of October 29, 1982. The fuel:air ratio was relatively high at 0.84, output was 83% of nameplate capacity, and the operating conditions set for enhanced tar production.

Table 2 presents an analysis of the poplar chip feedstock with a moisture content of 10.5%.

The composition of the clean, dry producer gas (Table 3) shows that the methane concentration, at 3.2%, and the ethylene concentration, at 1.2%, are quite significant and therefore contribute to the relatively high heating value of the gas (6.9 MJ/m^3).

An analysis of the particulate emissions are given in Table 4, while Table 5 presents the analysis of the gasifier bottom char and the rejects from the bottom of the gasifier's cyclone. The majority of the particulates which were collected during the sampling of the raw producer gas were retained in a small-diameter, pre-filter cyclone which was maintained at 173°C and which has a particle cut-off of approximately 5 microns. Most of the rest were caught on a filter maintained at 200°C. These particles have been acetone extracted to remove the soluble tar component. The particles consisted of about 22% ash, 30% fixed carbon, and 48% acetone-insoluble, highboiling organics.

Table 5 presents analyses for the gasifiers bottom char and the cyclone rejects. These materials have high calorific values (3.0 and 2.4 MJ/kg, respectively) which reflect their high carbon content. The bottom char consists mainly of fixed carbon (72%), while the cyclone rejects have a higher volatile organic and a higher ash component. The char accounts for 14% of the total energy (including the energy content of the producer gas), and 15% of the total carbon leaving the gasifier system. There is an opportunity for carbon recycling here. Obviously the cyclone rejects are a better "sink" for the inorganic ash than the bottom char and could be discarded.

A summary of the analysis of the condensate (pyroligneous acid) is shown in Table 6. The major components of this material are organic acids, with methanol and formaldehyde also being present in significant amounts (Table 7). The total organic carbon (TOC) content of the condensate was measured in order to provide data for a gasifier carbon balance. It is noted from Table 7 that most (75%) of the TOC has been accounted for by relatively few organic compounds.

The condensate is acidic (pH = 3.6) with a high (132,000 mg/L) COD (chemical oxygen demand). The ratio of COD/TOC was essentially constant at 2.38 for all of the testing work on this gasifier and is close to the theoretical value of 2.67 for complete combustion of carbon. The condensate is a good solvent for many plastics as will be discussed in a further section.

Table 8 presents the ultimate analyses and the calorific value for the tars. Tars are arbitrarily defined to be a complex mixture of organic compounds which are non-soluble in water but soluble in acetone. Twenty percent of the tars were collected at a temperature of approximately 200°C, while the other 80% condensed out at a temperature between 20°C and 200°C. The carbon:hydrogen ratio of these two fractions was similar. Major polycyclic aromatic hydrocabon compounds, as determined by gas chromatography and listed in Table 9, are the xylenes and naphthalene. Other polycyclic aromatic hydrocarbons and their atmospheric boiling points are also identified in this table. It is apparent that even the high boiling point compounds have a significant vapour pressure at the sampling train filter temperature (200°C) and therefore pass through to be collected by the condensor/impinger system. The large fraction of low boiling xylene compounds which were collected before and on the filter are thought to have absorbed onto the char particles which were collected in these areas.

The gasifier mass balance (Table 10) was obtained by adjusting the air flow to the gasifier so as to close the nitrogen balance. (This flow rate is not accurately monitored.) The resultant balances are seen to be quite precise.

Table 11 presents a detailed description of the contribution of inflow and outflow streams to mass, energy, and element balances. (The energy balance is relative to 15°C, 1 atm.) It is apparent from Table 11 that the distribution of carbon in the output streams is a reasonably good surrogate for the distribution of energy. The major energy loss (14%) was in the bottom char while the fly ash (cyclone rejects) accounted for less than 1% of the total energy and hence could be disposed of (no recycle) without significantly reducing the overall energy efficiency.

The estimation of gross and net energy conversion efficiencies is shown in Table 12. Gross energy efficiency is the ratio of the total energy of the hot, raw producer gas divided by the total input energy. Net energy efficiency, on the other hand, is the ratio of the higher heat of combustion of the clean, dry producer gas divided by the total input energy. Under the conditions which the test gasifier operated a significant fraction of the raw producer gas energy was due to the energy content of the tar, particulates, and condensates. For an internal combustion engine this material would have to be scrubbed out and hence the net energy conversion efficiency would be more appropriate.

3.0 FLUIDIZED-BED GASIFIER PRODUCT STREAM

This section will, for purposes of comparison, present a detailed description of the product streams from a fluidized-bed gasifier. The gasifier, designed and operated by B.C. Research, was operated so as to increase tar production above normal rates. This was done during the development phase of a new gasifier sampling apparatus (ENFOR C-172). The fluidized-bed consisted of approximately 20cm of 0.6 - 0.8 mm quartz sand.

Table 13 gives the operating conditions during a test run. Sampling was done in the upper free-board zone in order to expose the prototype sampler to an elevated temperature. An analysis of the alderwood sawdust used as biomass feed is shown in Table 14. Table 15 tabulates the dry producer gas analysis.

The results of the particulate analysis (Table 16) indicate that over 60% of the material in the upper free-board had an AED (aerodynamic equivalent diameter) of greater than approximately 5 microns (the cyclone cut-off diameter). At least 8% by weight would have been less than 5 microns in diameter and hence would be difficult to remove by conventional scrubbers.

The condensate analysis (Table 17) shows that the condensate is slightly basic (pH = 7.85). This is thought to be caused by the ammonia generated during gasification of the hardwood feedstock which contains 0.3% nitrogen. A simple calculation gives the potential ammonia production as 14.7 equivalents/hour while the measured organic acid production (as acetic acid) was only 0.1 equivalents/hour. Nitrogen measured in the condensate was 5 equivalents/hour, expressed as ammonia.

The chemical oxygen demand (COD) was high at 18,000 mg/L. The ratio of COD to total organic carbon (TOC) was almost constant for all runs, at 2.2, even though the individual values varied between runs by a factor of four.

The tar analysis (Table 18) show that the tar composition, based on ultimate analysis, is comparable before and after the 200°C heated filter. A more detailed analysis of a similar tar sample is presented in Table 19. Most of the carbon is shown, by NMR-C^{13} analysis, to be in the aliphatic or the aromatic form. The acetone soluble tar is only partially soluble in other common solvents.

The overall mass balance and the overall energy balances are presented in Tables 20 and 21, respectively. Table 22 tabulates the fractional contribution of each stream to the mass and energy flows. The carbon and energy content of the particulates appear to be minor while for the tar they represent a significant loss.

4.0 COMPARISON OF BIOMASS GASIFIERS

The previous two sections presented a detailed description of the product stream from a down-draft gasifier (Forintek) and from a fluidized-bed gasifier (B.C. Research). These two gasifiers were choosen to represent the genre because of the availability of a large amount of their test data in the literature.

4.1 PRODUCER GAS QUALITY AND ENERGY CONVERSION

A comparison of these two gasifiers, plus five others for which adequate data are available, is shown in Table 23. (Data sources are referenced in Table 24.) The fuel:air ratio and dry gas higher heating value (MJ/m^3) are seen to vary widely between gasifiers (approx. 300%). However, if the producer gas quality is normalized by simply dividing it by the fuel:air ratio, then the resulting deviation is reduced to 16%. The very strong relationship between these two parameters is further illustrated by the experimental line in Figure 1, which also plots theoretical relationships between caloric value and fuel to air ratio. The theoretical curve shown in Fig. 1 identified as Queen's University simulation model (Bacon et al, 1981) was calculated for a fluidized-bed wood gasifier, based on 100% carbon conversion and a fuel feed composition of 0.52 C, 0.062 H and 0.418 O on a dry weight basis. One of the underlying assumptions for the calculation is that the gasification reactions reach a certain degree of thermodynamic equilibrium. This is being done by taking the following three independent reactions

$$C + CO_2 = 2CO$$
$$C + H_2O = CO + H_2$$
$$C + 2H_2 = CH_4$$

and modifying the equilibrium constant formuation. Each of the free energies of formation of CO_2, H_2O and CH_4 in the pseudo-equilibrium constant equations is multiplied by a factor α_i. The choice of numerical values of α_i has been determined

from the performance data of different wood gasifiers; they are 0.99, 1.0 and -1.8 for $\alpha(CO_2)$, $\alpha(H_2O)$ and $\alpha(CH_4)$ respectivly. When equilibrium approaches, $\alpha_i = 0$; when $\alpha_i = \infty$ (or $\alpha[CH_4] = -\infty$) it implies no reaction. It should also be noted that even though the curve in Fig. 1 represents the results of fluidized-bed simulation, the effects of types of gasifiers have been shown to be minor (Bacon et al, 1981). The curve can be served as a basis for comparison of calorific values of different gasifiers.

The downdraft and updraft gasifiers are seen to operate at a much higher fuel to air ratio than the fluidized-bed units and therefore produce a higher quality of gas. The Queen's University Simulation Model indicates that there is little or no direct effect of fuel moisture content upon gas quality.

The effect of the fuel:air ratio on the net energy conversion efficiency is graphically illustrated in Figure 2. Major deviations from the dashed line (Queen's University computer simulation of a fluidized-bed gasifier) will be caused by significant tar and non-recycled char production. This is obvious in the lower of the two Forintek Biomass data points (25% char production) and the Westwood Polygas data point (24.2% of the carbon tied up on tar and other condensable organics). ECO data also falls below the theoretical value. Even though only 3.6% of char/particulates was reported, in view of low dry fuel/air ratio this amount of char/particulates formation is still significant.

For SPC Imbert gasifier, the lower part of the gasifier was filled with char before start-up. Part of the char participates in the gasification reactions. Thus the net amount of char produced in a run is not accountable. Low calorific value of the producer gas could still be caused by the problem of excessive char formation.

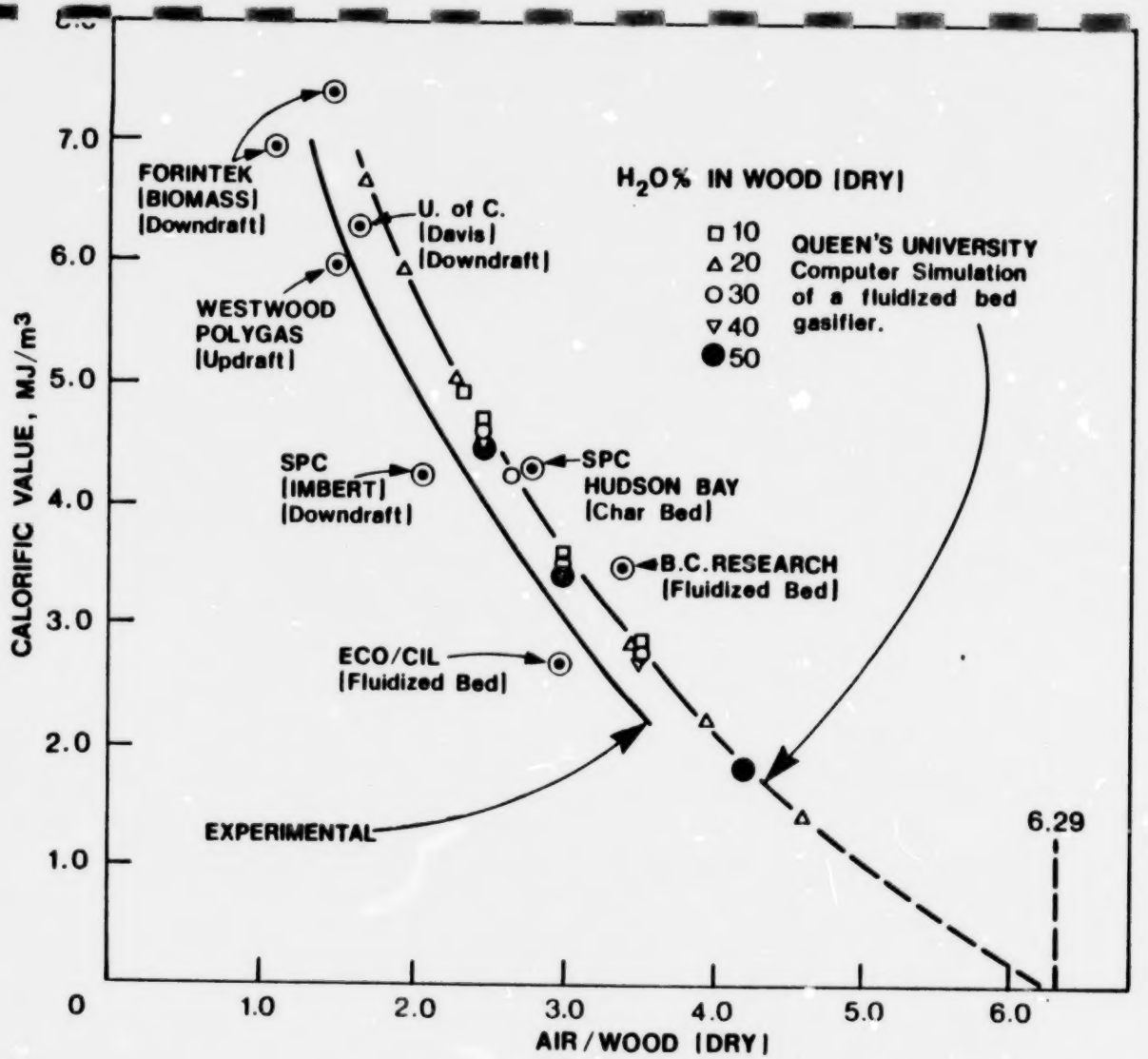

FIGURE 1

CALORIFIC VALUE OF THE PRODUCT GAS VERSUS AIR / DRY WOOD RATIO

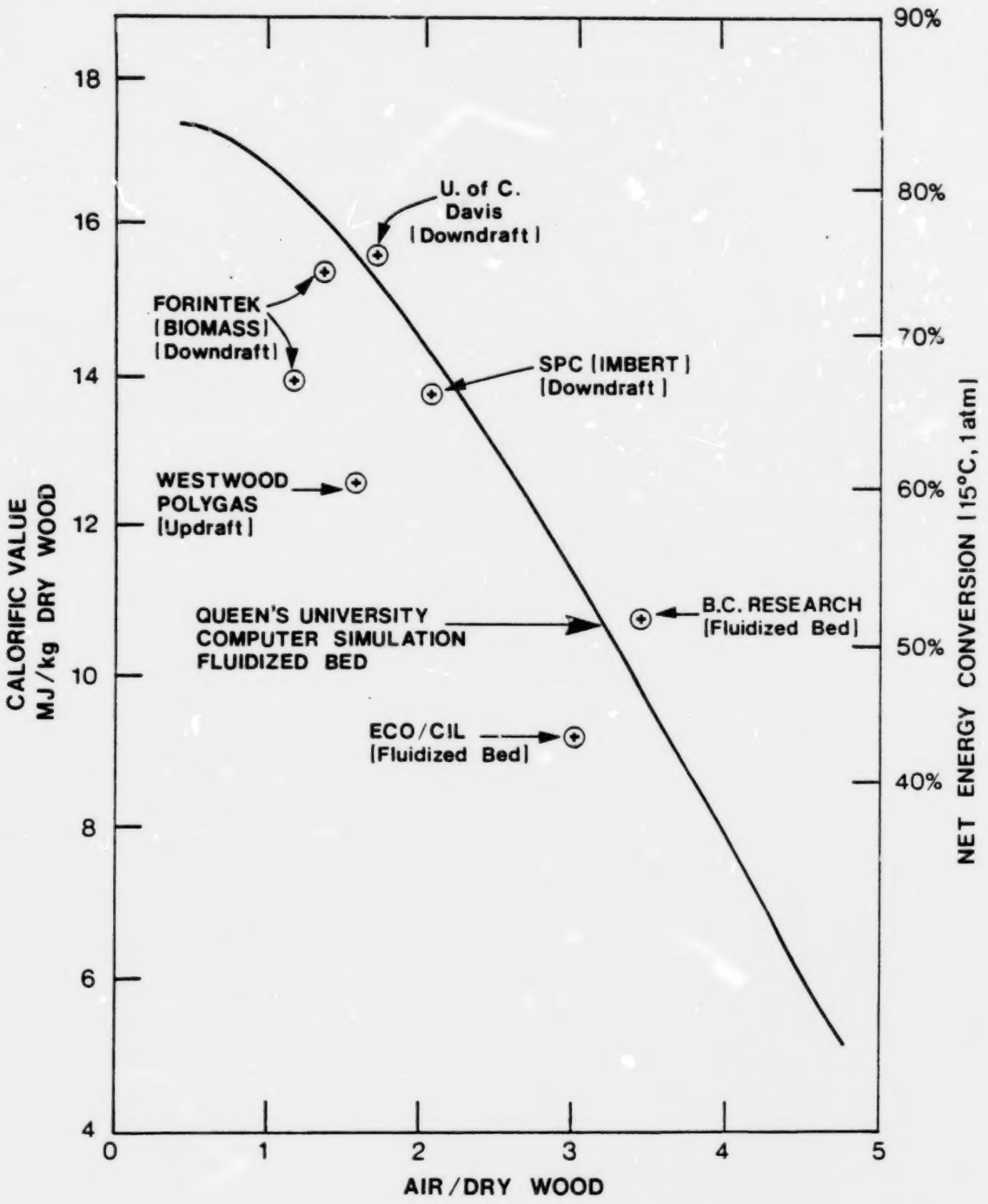

FIGURE 2

CALORIFIC VALUE PER UNIT MASS OF DRY WOOD GASIFIED AND NET ENERGY CONVERSION VERSUS AIR/DRY WOOD RATIO.

An inspection of Table 23 fails to reveal any trend between the concentration of methane in the dry producer gas, and the other gasifier parameters.

4.2 TAR AND CONDENSABLES

Biomass is subjected to different processes within the gasifier: drying, pyrolysis, and gasification. Energy for these processes is derived mainly from the partial oxidation of char ($C + O_2 \rightarrow CO_2$; -394 kJ/mole). Other reactions (gasification and water shift) tends to balance each other in maintaining a stable reaction temperature.

In the case of the updraft (counter-current) gasifier, for example the Westwood Polygas gasifier, much of the volatilized tars and pyroligneous acids is carried up and out of the reactor in the form of a mist.

These condensables are therefore not exposed to the high temperature oxidation zone as they are in a downdraft (cocurrent) gasifier and are therefore not subjected to the cracking and gasification reactions which occur there. The amount of condensable tars emitted from a fluidized-bed gasifier, on the other hand, are expected to be relatively low if a well behaved fluidization is maintained and if the bed temperature is adequate (approx. 800°C) (Overend, 1982).
In the comparison of Table 23, we see that these expectations are generally realized: an updraft gasifier converts approximately 24% of its feed carbon to tars and condensables; a downdraft gasifier about 11% (when measured); and a fluidized-bed varying amounts, depending mainly on bed temperature and the condition of fluidization.

The composition of the condensable organic stream is such that this material is corrosive to many materials, is toxic and mutagenic, and should not be allowed to be emitted to the environment without prior treatment.

The condensate from a downdraft gasifier fed with poplar chips is rich with phenols, organic acids, methanol, and formaldehyde (Table 6 & 7) while that from a fluidized-bed gasifier fed with alderwood sawdust contains a lower proportion of the organic acids and is actually slightly basic (pH 7.85), due to fuel nitrogen. The measured ratio of chemical oxygen demand to total organic carbon (COD/TOC) for these two gasifiers was almost identical at about 2.3.

Table 25 presents a list of common plastics and their resistance to some of the chemicals which constitute the condensate.

Generally PVC and related plastics are not recommended, whereas high density polyethylene and polypropylene are acceptable at 60°C. The acidic condensates are also corrosive to carbon steel; 304 stainless steel would be acceptable. Any system designed to accommodate the pyroligneous acid and tar from biomass gasification should give careful consideration to their corrosive nature.

A comparison of tar components from different gasifiers has been previously attempted; extreme analytical problems were encountered (Duncan, 1981). Table 19 presents more recent data on tar analysis as carried out by Dr. Hughes Menard (University of Sherbrooke). It is seen that most of the tar is in the form of aromatic and aliphatic carbons and is relatively insoluble in many common solvents.

Most of the tar from a downdraft gasifier was collected after the 200°C sampling filter (Table 8) while that from the fluidized-bed gasifier was equally split between the front-half (high-temperature) part of the sampling train and the back-half (low-temperature) region of the sampler.

This observation infers that the fluidized-bed gasifier may generate a higher fraction of high boiling tars than does the downdraft gasifier. This is reasonable considering the cracking of large molecules which occurs in the oxidation zone of the downdraft gasifier.

A comparison of the concentration of selected polycyclic aromatic hydrocarbons in the tar is listed in Table 9. The concentration of low boiling xylenes is significantly higher in the tar from the Forintek downdraft gasifier otherwise the polycyclic aromatic hydrocarbons profiles are similar. The quantified presence of known carcinogens and mutagens substantiates the positive results of previous mutagenicity tests (Duncan, 1981).

5.0 CONCLUSIONS AND RECOMMENDATIONS

A comparison of the producer gas quality and the energy conversion efficiency of various gasifier shows that these parameters are predicated by the fuel to air ratio as predicted by the Queen's University Computer Simulation Model. Better performance from fluidized-bed gasifiers can only be obtained through strategies to increase this ratio.

Mathmatical modelling is a powerful tool for predicting gasifier performance. Further work is recommended on the existing simulation models to allow for finite tar production and to examine strategies such as combustion gas recycling.

Dynamic modelling is also useful for the examination of gasifier transients and design of effective control systems.

Both the downdraft and fluidized bed gasifiers produce a dirty, corrosive, toxic, and mutagenic raw producer gas which must usually be treated before being further processed or combusted.

A significant fraction of the particulates (acetone insoluble) from both gasifiers was less than about 5 microns in diameter and hence would be difficult to scrub out with low energy scrubbers.

Tars will condense out in all of the lower temperature components which follow a gasifier. In the case of a downdraft gasifier the majority of the tars were collected below 200°C, while for a fluidized-bed gasifier, the proportions were equally divided above and below this temperature.

The water soluble condensed organics (pyroligneous acid) are corrosive, toxic, and have a high chemical oxygen demand.

Possible solutions to the tar and the pyroligneous acid problems are:

1. A special catalytic cracking section (expensive, may need reactivation, may plug, most suited to large fluidized-bed systems).

2. Volatilization and reinjection of all condensates (requires energy, only feasible for low moisture feed stocks).

3. Use enhanced char production to scrub organics out of the condensate, recycle char to the reactor, neutralize and sewer the polished condensate (char may have to be "activated", possible residual condensate toxicity - extra equipment required).

4. Biological treatment of the condensates using, for example a rotating biological contactor (expensive, may have to strip out ammonia first).

The third approach may be feasible for downdraft gasifiers. It is recommended that further development work be done in this area as the downdraft unit is finding increasing application in isolated communities in Canada. It is also strongly recommended that available data be used in an economic comparison of commercial downdraft gasifier gensets and diesel powered gensets. In this way components in the cost of biomass gasification can be quantified and areas for improvement identified.

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Table 1

DOWNDRAFT GASIFIER OPERATING CONDITIONS

Manufacturer	Biomass Corporation (Yuba City, Calif.)
Rating (output)	1055 MJ/hr
Test Location	Forintek Canada Corp. (Ottawa, Ontario)
Test Date	October 29, 1982
Feed Type	Poplar chips
Feed Moisture (% wet.)	10.5
Feed Rate (kg/hr wet.)	73.0
Air Input (kg/hr)	78.63
Fuel/Air Ratio (Dry)	0.837
Temperatures (°C)	
Above grate	680°
Below grate	550°
Drying zone	160°
Dry Gas Quality (MJ/m^3)*	6.94
Dry Gas Methane Content (%)	3.2
Particulate Emissions (kg/hr)	0.272

* 15°C, 1 atm.

Table 2

POPLAR CHIP FEED ANALYSIS (Bone Dry Basis)

Moisture	10.5%
HHV (kJ/kg dry wood)	19050
Ash	0.5%
Carbon	48.5%
Oxygen	45.3%
Hydrogen	6.2%
Nitrogen	<0.1%
Sodium	7 ppm
Potassium	7 ppm

Table 3

DOWNDRAFT GASIFIER
DRY PRODUCER GAS ANALYSIS
(% By Volume)

Hydrogen	16.9
Oxygen	0.9
Nitrogen	42.3
Methane	3.2
Ethane	0.1
Ethylene	1.2
Carbon Dioxide	11.4
Carbon Monoxide	24.4

Table 4

PARTICULATE ANALYSES
(Downdraft Gasifier)

SAMPLE	WEIGHT DRY g	ASH % dry basis	CALORIFIC VALUE kJ/kg dry	CARBON dry basis %	CARBON dry basis g	HYDROGEN dry basis %	HYDROGEN dry basis g	OXYGEN (a) dry basis %	OXYGEN (a) dry basis g	VOLATILES (b) % dry basis	FIXED CARBON (b) % dry basis	SODIUM (c) AND POTASSIUM % dry basis
Prefilter	1.25	21.5	9430	63.8		2.1		32.4		48.7	29.7	1.7
Filter	0.62		8360									
Postfilter	0.04											
TOTAL	1.91	21.5	9080	63.8	1.22	2.1	0.04	32.4	0.62			

a) Oxygen calculated: [100 - ∑C + H + Na + K]
b) From thermograms: weight loss in nitrogen atmosphere = volatiles; subsequent weight loss in oxygen = fixed carbon
c) Na and K results from char analysis
d) CV, C and H determined for prefilter particulates; same values used for filter and postfilter particulates

Table 5

BOTTOM CHAR AND CYCLONE REJECTS ANALYSES
(Downdraft Gasifier)

SAMPLE	MOISTURE %	ASH dry basis %	CALORIFIC VALUE dry basis kJ/kg	CARBON dry basis %	HYDROGEN dry basis %	OXYGEN (a) dry basis %	NITROGEN dry basis %	SODIUM dry basis %	POTASSIUM dry basis %	VOLATILES (b) dry basis %	FIXED CARBON dry basis %
Bottom Char	2.5	5.0	30280	91.0	0.3	4.2	0.2	0.1	0.3	18.3	76.8
Cyclone Rejects	9.5	17.5	24220	72.7	1.5	18.7	0.2	0.1	0.7	23.6	58.8

a) Oxygen measured
b) From thermograms: weight loss in nitrogen atmosphere = volatiles; subsequent weight loss in oxygen = fixed carbon

Table 6

SUMMARY OF CONDENSATE ANALYSIS
(Downdraft Gasifier)

pH	3.6
Total Organic Carbon (mg/L) (TOC)	55450
Chemical Oxygen Demand (mg/L) (COD)	131900
COD/TOC Ratio	2.4
Total Acidity (eq/L)	0.60
Phenols (mg/L as phenol)	4990
Organic Acids (mg/L as acetic)	37430
Methanol (mg/L) *	15310
Acetone (mg/L)	3550
Tannin and lignin (mg/L as tannic acid) **	7040

* ethanol not detected in the condensate samples
** determined on residue after distillation of phenols

Table 7

COMPOSITION OF CONDENSATES: MAJOR COMPONENTS
(Downdraft Gasifier)

COMPOUND	RUN 3	
	g compound/100 mL condensate %	g carbon/100 g TOC % *
Phenols (as phenol)	0.50	6.9
Acetic Acid	4.29	30.9
Propionic Acid	0.45	3.9
Methanol	1.53	10.3
Acetone	0.35	4.0
Formaldehyde	1.77	12.8
Tannin and Lignin (as tannic acid) **	0.70	6.6
Unknown	-	24.5

* TOC: Total Organic Carbon
** nonvolatile hydroxylated aromatics

Table 8

TAR ANALYSIS
(Downdraft Gasifier)

SAMPLE	WET WEIGHT	WATER CONTENT	DRY WEIGHT	ASH dry basis	CALORIFIC VALUE	CARBON dry basis		HYDROGEN dry basis		OXYGEN (a) dry basis		NITROGEN (b) dry basis	
	g	%	g	%	kJ/kg dry tar	%	g	%	g	%	g	%	g
Prefilter*			3.29	0.5	33000	66.5	2.25	10.3	0.35	23.2	0.79		
Postfilter*	20.84	35.0	13.55	0.1	23780	69.2	9.38	9.9	1.33	20.6	2.79	0.4	0.1
TOTAL			16.94		25630		11.6		1.68		3.58		0.1

a) Oxygen calculated: [100 - ∈C + H + N]
b) Nitrogen determined on postfilter samples only
c) Prefilter tar samples evaporated to dryness

* Prefilter: nozzle, probe, cyclone, gas conditioning coil and filter assembly
Postfilter: condenser and impinger

Table 9

ANALYSIS OF TAR BY GAS CHROMATOGRAPHY
IDENTIFICATION OF POLYCYCLIC AROMATIC HYDROCARBONS

COMPOUND	B.C. RESEARCH FLUIDIZED-BED GASIFIER	FORINTEK DOWNDRAFT GASIFIER		BOILING POINT
		Prefilter	Postfilter	
	mg/g	mg/g	mg/g	°C
Toluene	nd*	0.031	nd	111
m-,p-xylene	0.34	6.10	13.21	139
o-xylene	0.20	6.93	9.26	144
Cumene	0.56	0.075	nd	152
Trimethyl benzene	nd	0.60	0.32	-
p-cymene	0.24	nd	0.59	-
Indene	3.29	0.12	3.07	183
Tetralin	0.36	nd	0.88	-
Naphthalene**	10.60	0.47	16.18	218
Biphenyl**	nd***	0.50	1.30	255
Acenaphthene**	4.23	0.082	8.65	270
Fluorene	1.21	0.071	1.87	294
9,10-dihydrophenanthrene	0.90	0.43	6.95	-
Phenanthrene**	2.63	0.048	3.76	338
Anthracene**	1.04	0.027	1.06	340
Fluoranthene**	0.89	0.036	1.57	383
Pyrene**	0.77	0.031	1.27	393
Benz(a)anthracene**	0.36	0.023	0.33	435
Chrysene	0.36	0.011	0.36	441
Benzo(k)fluoranthene	0.20	0.015	0.17	481
Benzo(b)fluoranthene	0.59	0.043	nd	481
Benzo(a)pyrene	0.21	0.033	nd	496
Indeno(1,2,3-cd)pyrene	0.21	0.037	0.36	-
Benzo(ghi)perylene	0.18	0.027	nd	-

* not detected
** presence of compound confirmed by GC-MS analysis carried out by Dr. Hughes Ménard, University of Sherbrooke
*** large peaks either side of biphenyl peak prevented quantification

B.C. Research Fuel: Alderwood Sawdust (38.3% moisture)
Forintek Fuel: Poplar Chips (10.5% moisture)

Table 10

MASS BALANCE (Downdraft Gasifier)
(Date: 10/29/82)

FUEL MOISTURE 10.5%	kg/hr INPUT		kg/hr OUTPUT		% CLOSURE
	Wet Fuel	Humid Air	Clean Gas	Others	
Overall	73.02	78.62	127.19	42.17	112.0
Carbon	31.66	0	25.12	7.88	104.2
Hydrogen	4.90	0.06	2.63	2.46	102.6
Oxygen	36.46	18.57	39.45	18.29	104.9
Nitrogen	0.03	59.98	59.99	0.02	100.0

Table 11

CONTRIBUTION OF INFLOW AND OUTFLOW STREAMS TO MASS, ENERGY AND ELEMENT BALANCES (Downdraft Gasifier)

	MASS BALANCE %	ENERGY BALANCE %	CARBON %	HYDROGEN %	OXYGEN %	NITROGEN %
INPUT						
Dry Feed	43.1	99.8	100.0	81.4	53.8	0.1
Moisture in Feed	5.1	0	0	17.4	12.4	0
Air	51.5	0	0	0	32.9	99.9
Moisture in Air	0.3	0.1	0	1.2	0.9	0
(Process Energy Input)	-	0.1	-	-	-	-
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0
OUTPUT						
Dry Clean Gas	74.9	71.9	76.1	51.7	68.3	100.0
Moisture in Gas	10.8	4.2	0	40.1	28.3	0
Particulates	0.2	0.2	0.6	0.2	0.2	0
Tar	1.4	5.3	5.0	4.7	0.9	0
Condensate	9.2	3.3	2.6	2.9	1.6	0
Char	3.2	14.0	15.0	0.4	0.4	0
Fly Ash	0.2	0.6	0.7	0	0.1	0
Moisture in Char and Fly Ash	0.1	0	0	0	0.2	0
(Process Heat Loss)	-	0.5	-	-	-	-
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0

Table 12

ENERGY BALANCES (Downdraft Gasifier)

INPUT (MJ/hr)						OUTPUT (MJ/hr)						
Fuel	%	Air	%	Others	%	Clean Gas	%	Tar Particulates Condensate	%	Others	%	
1243.7	99.8	0.76	0.1	1.61	0.1	900.22	76.1	104.27	8.8	178.67	15.1	CLOSURE = 95.0%
GROSS EFFICIENCY												
1243.70	99.8	0768	0.1	1.61	0.1	900.22	89.6	104.27	10.4	0	0	GROSS EFFICIENCY = 80.6%
NET EFFICIENCY												
1243.70	99.8	0.76	0.1	1.61	0.1	825.94*	100.0	0	0	0	0	NET EFFICIENCY = 66.3%

* Heat of combustion; dry, clean gas.

Table 13

FLUIDIZED-BED GASIFIER OPERATING CONDITIONS

Test Site	B.C. Research
Sampling Location	Upper free-board
Rating (nominal output)	500 MJ/hr
Test Date	June 29, 1982
Feed Type	Alderwood sawdust
Feed Moisture (% wet)	27.67
Feed Rate (kg/hr wet.)	65.86
Air Input (kg/hr)	163.83
Fuel/Air Ratio (Dry)	0.29
Temperatures (°C)	
Bed	785°
Sample location	601°
Dry Gas Quality (MJ/m^3)*	3.52
Dry Gas Methane Content (%)	2.8
Particulate Flux (kg/hr)	0.77

* 15°C, 1 atm.

Table 14

WOOD ANALYSIS
(Alderwood sawdust)

WATER	ASH	Weight %* C	H	N	O	CALORIFIC VALUE kJ/kg
27.7	0.8	47.3	6.1	0.3	46.3	17 850

Table 15

DRY GAS ANALYSIS
(Fluidized-Bed Gasifier)

GAS	% BY VOLUME	GAS	% BY VOLUME
CH_4	2.8	N_2	56.0
CO	17.2	CO	9.2
C_2H_4	1.1	H_2	5.0
C_2H_6	0.1	C_3H_8	0
O_2	1.8		

Table 16

RESULTS OF PARTICULATE ANALYSIS
(Fluidized-Bed Gasifier)

DISTRIBUTION	% TOTAL
Probe and nozzle wash	20.8
Cyclone wash	7.5
Cyclone catch	63.6
Coil and filter wash	1.2
Filter (dry)	6.3
Condenser tube and bottle wash	0.5
Condenser bottle wash	0.1
TOTAL	100.0

Of this total 55.9% was ash which contains 1.028 g sand carry-over and 1.410 g inorganic materials. The analysis of cyclone catch showed 46.4% of C, 0.6% of H, 0.5% of N, 12.9% of O, 0.9% of S and others. The calorific value was determined to be 10 395 kJ/kg.

Table 17

RESULTS OF CONDENSATE ANALYSIS
(Fluidized-Bed Gasifier)

COMPOUND	CONCENTRATION mg/L	ELEMENT			
		Wt.(mg)	C (mg)	H (mg)	O (mg)
Phenols (phenol)	3375	536.6	410.9	34.5	91.2
Organic acids (acetic)	257	40.8	16.3	2.7	21.8
Methanol	2141	340.4	127.6	42.8	170.0
Acetone	1628	258.8	160.6	26.9	71.3
TOTAL		1176.6	715.3	106.9	354.3
TOC	8086		1286.		
ADJUSTED TOTAL			1286.	192.3	636.9
COD	17930				

COD/TOC Ratio = 2.22 pH = 7.85

Table 18

RESULTS OF TAR ANALYSIS
(Fluidized-Bed Gasifier)

SAMPLE NO.	WET WT. g	WATER %	DRY WT. g	%C(b)	%H	%O(c)	%N(c)	CALORIFIC VALUE kJ/kg
1	9.500	0.3	9.473	66.6	11.6	17.5	0.3	33 375
2	7.895	0.3	7.873	72.9	9.9	17.5	0.3	34 657

a) Sample No. 1: Acetone washes before and inclusive of filter.
Sample No. 2: Acetone washes after filter.
b) Values on dry basis.
c) Based on analysis after filter.

Table 19

**RESULTS OF TAR ANALYSIS BY HIGH PERFORMANCE LIQUID CHROMATOGRAPHY
B.C. RESEARCH GASIFIER TAR SAMPLE
- RESULTS FROM DR. HUGHES MENARD,
UNIVERSITY OF SHERBROOKE**

A. WATER DETERMINATION

3.1% by weight of tar by Karl Fischer Technique

B. ELEMENTAL ANALYSIS

74.6% carbon
8.2% hydrogen
1.2% nitrogen
16.0% oxygen (by difference)

C. ACID ANALYSIS

Compound	% of tar by weight
Glycolic acid	0.0
Formic acid	0.2
Acetic acid	0.1
Propionic acid	5.3
Butyric acid	0.2
Pentanoic acid	0.4
Hexanoic acid	0.6
Heptanoic acid	0.6

D. NMR C^{13} ANALYSIS

Aromatic carbon	35.8% by weight
Aliphatic carbon	53.6%
Carbon tentatively allocated to sugars	7.4%
Carbonyl carbon	3.2%

E. FRACTIONATION

Solvent	% of Tar by Weight in Fraction
100% Pentane	31.0
100% Tetrahydrofuran	32.8
100% Methanol	2.9
100% Water	0.6
50% Water-50% Acetic Acid	10.3
Material retained on the column or lost during evaporation of solvent	22.4

Table 20

MASS BALANCE (Fluidized-Bed Gasifier)

	kg/hr INPUT		kg/hr OUTPUT		% CLOSURE
	Fuel	Air	Dry Gas	Others	
Overall	65.86	163.85	157.48	32.42	82.7
Carbon	22.55	0	20.42	2.75	102.7
Hydrogen	4.92	0.14	1.44	3.49	97.4
Oxygen	38.96	38.84	40.45	25.71	86.1
Nitrogen	0.15	124.88	95.12	0.10	76.2

Table 21

ENERGY BALANCE
(Fluidized-Bed Gasifier)

ENERGY IN, kJ/hr		ENERGY OUT, kJ/hr	
Feed, ht. of comb.	850 312	Dry gas, ht. of comb.	447 548
Process energy	6 710	Dry gas, sensible ht.	108 710
Process air	31	Water vapor	102 052
Feed moisture	702	Particulates, ht. of comb.	8 136
Dry feed, sensible heat	0	Tars, ht. of comb.	105 532
		Soluble Organics, ht. of comb.	10 907
		Process heat loss	1 060
TOTAL	857 755		783 944
% Closure	91.4		

Table 22

CONTRIBUTION OF INFLOW AND OUTFLOW STREAMS TO MASS, ENERGY AND ELEMENT BALANCES (a)
(Fluidized-Bed Gasifier)

DESCRIPTION	MASS BALANCE %	ENERGY BALANCE %	C %	H %	O %	N %
INPUT						
Dry feed	20.7	99.1	100.0	57.3	28.3	0.1
Moisture in feed	7.9	0.1	0	40.0	21.1	0
Air	70.8	0	0	0	49.1	99.9
Moisture in air (Process energy)	0.6	0.8	0	2.7	1.5	0
OUTPUT						
Dry clean gas	82.9	71.0	88.1	29.2	61.1	99.9
Moisture in gas	14.8	13.0	0.0	63.1	37.7	0
Particulates	0.4	1.0	1.6	0	0.1	0
Tar	1.6	13.5	9.3	6.9	0.9	0
Condensate (Process energy)	0.3	1.4	1.0	0.8	0.2	0.1
Overall Closure (%)	83	91	103	97	86	76
Energy Conversion Efficiency						
Gross	91%					
Net	52%					

(a) Reference conditions: 15°C, 1 atmosphere (per Iso/TC28-5024)

TABLE 23

COMPARISON OF BIOMASS GASIFIERS

GASIFIER TYPE	DOWNDRAFT	DOWNDRAFT	DOWNDRAFT	UPDRAFT	FLUID SAND BED	FLUID SAND BED	CHAR BED	FLUID SAND BED SIMULATION
REFERENCE	UNIVERSITY OF CALIF. (Davis)	SPC (Imbert)	FORINTEK (Biomass Corp.)	WESTWOOD POLYGAS	B.C. RESEARCH	ECO/CIL	SPC (Hudson Bay)	QUEEN'S UNIVERSITY
Dry Fuel: Air Ratio	0.59	0.47	0.84 (0.75)	0.66	0.29	0.32-0.35	0.36	0.40
Dry Gas Quality (MJ/M^3)*	6.2	4.2	6.9 (7.4)	6.0	3.5	2.6-2.8	4.3	4.7
Net Energy Conv. Efficiency (%)	76.	66.	66. (74.)	60.	52.	44.	(N/A)	72
Carbon Conv. Efficiency (%)	92.	96.	79. (75.)	76.	91.	91.	(N/A)	100
Fuel Type/ Moisture (%)	Walnut Shells 1.6	White Spruce Chips 10	Poplar Chips 10.5 (Chips 33.7)	Wood Chips 35.1	Alderwood Sawdust 27.6	Chips (41-42)	Aspen Chips 57	Wood Sawdust 20
Bed Temp. (°C)	Below Throat 870	Below Throat 890 Tuyeres 598 Char Bed 499	Char Bed 670 (N/A)	750-Pyrolysis 1300-Char	785	725-786	650 (Approx.)	800
Tar/Condensables (% Carbon Feed)	11	"Negligible"	10.8	24.2	10.6	(N/A)	"High" (20% of energy)	Assumed None
Char/Particulates (% Carbon Feed)	0.9	(N/A) Char "Recycled"	14.5 (25)	<1	1.6 (Freeboard Zone)	3.6	"Low"	Assumed None
Producer Gas Methane Conc. (%)	5.1	1.1 (0.6-1.4)	3.2	1.5	2.8	2.6-3.4	2.2	5.2
Notes	Mist in gas stream not analyzed	Data per ENFOR C-197a 75°C Air preheat	DATA per ENFOR C-172 (Run 3) (Data in brackets per Forintek tests)		Data per ENFOR C-172			Assumed 70°C Air preheat

*15°C, 1 atm.

Table 24

GASIFIER DATA SOURCES

1. University of California (Davis): Williams and Goss (1979).
2. S.P.C. (IMBERT): Van Der Heijden and Wild (1982).
3. FORINTEK (Biomass Corp.): Aiken and McDonald (1985).
4. FORINTEK (Biomass Corp.): L'Ecuyer and Huffman (1981).
5. WESTWOOD POLYGAS: Westwood Polygas Ltd. (1981).
6. B.C. RESEARCH: Esplin, Fung and Hsu (1985).
7. ECO/CIL: Gurnick, Luke and Hall (1980).
8. S.P.C. (Hudson Bay): Weisgerber and Van Der Heijden (1980).
9. QUEEN'S UNIVERSITY: Bacon, Downie, Hsu and Peters (1981).

Table 25

CHEMICAL RESISTANCE OF COMMON PLASTICS

CHEMICAL	PVC 60°C	CPVC 85°C	PP 60°C	PVDF 85°C	VITON 85°C	EPDM 60°C	PE(HD) 60°C	PTFE 85°C
Phenol	NR	-	R	R	R	R	R	R
Acetic Acid (20%)	NR	NR	R	R	NR	R	R	R
Formaldehyde (35%)	R	NR	R	R	NR	R	R	R
Methanol	NR	-	R	R	NR	R	R	R
Acetone	NR	NR	R	NR	NR	R	R	R

PVC - Polyvinyl chloride - not resistant to aromatics. Max. temp. 60°C.
CPVC - Chlorinated Polyvinyl Chloride - per PVC but max. temp. 90°C.
PE(HD) - High Density Polyethylene - resistant to most organics. Max. temp. 60°C.
PP - Polypropylene - similar to PE. Max. temp. 90°C.
PVDF - Polyvinyldene Fluoride. Max. temp. 140°C.
EPDM - Ethylene Propylene Rubber. Unsuitable for oils and fats. Max. 90°C.
PTFE - Polytetrafluoroethylene (eg. Teflon). Max. 250°C.